Year: 2017

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DOI: https://doi.org/10.1002/2016JG003728

Originally published at:
Xie, Jing; Kneubühler, Mathias; Garonna, Irene; Notarnicola, Claudia; De Gregorio, Ludovica; de Jong, Rogier; Chimani, Barbara; Schaepman, Michael E (2017). Altitude-dependent influence of snow cover on alpine land surface phenology. Journal of Geophysical Research: Biogeosciences, 122(5):1107-1122.
DOI: https://doi.org/10.1002/2016JG003728

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Biogeosciences

RESEARCH ARTICLE

10.1002/2016JG003728

Key Points:

- Snow cover duration shows strong correlation with start and length of the alpine growing season at high altitudes (above 2000 m)
- The correlation differences between climatic subregions and terrain aspects are more pronounced below 2000 m than above
- The correlation between start and length of the growing season and snow cover duration is strongest in natural grasslands

Supporting Information:

- Supporting Information S1
- Figure S1
- Table S1

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Citation:

Xie, J., M. Kneubühler, I. Garonna, C. Notarnicola, L. De Gregorio, R. De Jong, B. Chimani, and M. E. Schaepman (2017), Altitude-dependent influence of snow cover on alpine land surface phenology, *J. Geophys. Res. Biogeosci.*, *122*, doi:10.1002/2016JG003728.

Received 22 NOV 2016
Accepted 23 APR 2017
Accepted article online 1 MAY 2017

Altitude-dependent influence of snow cover on alpine land surface phenology

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Abstract Snow cover impacts alpine land surface phenology in various ways, but our knowledge about the effect of snow cover on alpine land surface phenology is still limited. We studied this relationship in the European Alps using satellite-derived metrics of snow cover phenology (SCP), namely, first snow fall, last snow day, and snow cover duration (SCD), in combination with land surface phenology (LSP), namely, start of season (SOS), end of season, and length of season (LOS) for the period of 2003–2014. We tested the dependency of interannual differences (Δ) of SCP and LSP metrics with altitude (up to 3000 m above sea level) for seven natural vegetation types, four main climatic subregions, and four terrain expositions. We found that 25.3% of all pixels showed significant ($p < 0.05$) correlation between ΔSCD and ΔSOS and 15.3% between ΔSCD and ΔLOS across the entire study area. Correlations between ΔSCD and ΔSOS as well as ΔSCD and ΔLOS are more pronounced in the northern subregions of the Alps, at high altitudes, and on north and west facing terrain—or more generally, in regions with longer SCD. We conclude that snow cover has a greater effect on alpine phenology at higher than at lower altitudes, which may be attributed to the coupled influence of snow cover with underground conditions and air temperature. Alpine ecosystems may therefore be particularly sensitive to future change of snow cover at high altitudes under climate warming scenarios.

1. Introduction

Vegetation phenology has been referenced as an important and observable track in ecosystem response to climate change [*Menzel et al.*, 2006] and as a key determinant of coupled water and land surface carbon exchange [*Barrio et al.*, 2013; *Richardson et al.*, 2010], as well as of species distributions [*Chuine and Beaubien*, 2001]. Furthermore, interannual variability in vegetation phenology affects the exchange of energy, water, and carbon between the vegetation and the atmosphere [*White et al.*, 2009]. With snow cover phenology (SCP) being among important climate drivers, changes in SCP have been reported to significantly influence the global energy balance [*Chen et al.*, 2015a, 2015b; *Euskirchen et al.*, 2007] and water cycling [*Barnett et al.*, 2005; *Rawlins et al.*, 2006], which has in turn implications on land surface phenology (LSP) [*Dorrepaal et al.*, 2003; *Monson et al.*, 2006; *Shimamura et al.*, 2006]. For instance, seasonal thawing and snowmelt affect the potential production and growing season length of vegetation at midnorthern latitudes [*Walker et al.*, 2014]. Plants adapted to changes in the duration of snow cover (such as snowbed or fellfield) can show distinct responses to snowmelt advancement or delay [*Keller and Körner*, 2003; *Wipf and Rixen*, 2010; *Wipf et al.*, 2006].

Alpine snow cover plays a significant role in the global climate system [*Intergovernmental Panel on Climate Change (IPCC)*, 2007] and a major role in regulating mountain ecosystems [*Jonas et al.*, 2008]. The dates of alpine plant growth respond to the change of climate and climate-related drivers such as snow cover [*Jonas et al.*, 2008; *Wipf and Rixen*, 2010]. Snow cover can regulate the growth of alpine vegetation and block off sunlight needed for photosynthesis. On the other hand, snow protects vegetation from dry and severe cold conditions and simultaneously supplies moisture [*Desai et al.*, 2016; *Ide and Oguma*, 2013; *Inouye*, 2008]. Annual change of snowmelt or snow cover may induce strong ecosystem responses. Together with other environmental factors, snow is one of the essential environmental parameters controlling high-altitude vegetation phenology [*Cornelius et al.*, 2013; *Wipf et al.*, 2009]. For instance, the first and last snow days were observed to be highly correlated with the end and start of growing season at high-altitude drier regions in Nepal Trans Himalaya [*Paudel and Andersen*, 2013].

An increase in annual mean temperatures of about 1.1°C has been observed in the European Alps over the past 100 years [*Böhm et al.*, 2001]. The expected continuation of this warming is likely to result in more frequent early snowmelt events [*Foppa and Seiz*, 2012]. The resulting reduction in snow cover may intensify water stress and ultimately constrains vegetation growth [*IPCC*, 2007]. Interacting with air temperature, variations in seasonal snow cover may affect plant growth [*Yu et al.*, 2013]. For instance, winter warming could result in snow fall reduction, or reduction in the duration of snow cover, thereby increasing soil freezing [*Groffman et al.*, 2006] and root mortality [*Peng et al.*, 2010; *Wahren et al.*, 2005], which in turn leads to a delay in the start of the growing season and a reduction of the vegetation growth [*Grippa et al.*, 2005]. Changes in seasonal patterns of snow are related to plant photosynthesis and growth in the snow-free season [*Galvagno et al.*, 2013; *Rossini et al.*, 2012], thus influencing ecosystem functioning [*Saccone et al.*, 2012]. Therefore, quantifying the relationship between snow cover and alpine phenology is crucial to understanding the mechanism of vegetation dynamics in alpine regions and monitoring of alpine phenology is necessary to assess the impact of seasonal snow extension and ongoing climate change.

Numerous studies have focused on snow-vegetation interaction in alpine environments [*Abeli et al.*, 2011; *Badeck et al.*, 2004; *Desai et al.*, 2016; *Jonas et al.*, 2008;, *Keller et al.*, 2005; *Paudel and Andersen*, 2013; among others]. Recently, a number of studies have focused on the relationship between snow and vegetation in different regions [e.g., *Dye and Tucker*, 2003, *Peng et al.*, 2010], investigating the effect of snow on tundra [e.g., *Dorrepaal et al.*, 2003; *Wahren et al.*, 2005; *Wipf et al.*, 2006, 2009], grass, and meadow [e.g., *Cornelius et al.*, 2013; *Zeeman et al.*, 2017] and forest [e.g., *Jönsson et al.*, 2010; *Hu et al.*, 2010; *Trujillo et al.*, 2012]. Efforts have been made to investigate the effects of changing snow cover on alpine vegetation phenology by means of direct snow manipulation experiments [*Cornelius et al.*, 2013; *Wipf and Rixen*, 2010]. A majority of former snow-vegetation field experiments and studies in the Alps focused primarily on small-scale measurements [e.g., *Abeli et al.*, 2011; *Julitta et al.*, 2014; *Keller et al.*, 2005; *Saccone et al.*, 2012; *Wipf et al.*, 2009]. However, the effect of snow cover changes on variation of alpine phenological events at the ecosystem scale across altitudinal gradients is not well known yet. While plot-scale ground monitoring can accurately report on plant phenology at small scale [*Fisher et al.*, 2006], satellite observations can also provide accurate observations of snow-vegetation relations at large scale. Remote sensing data are increasingly important in spatiotemporal research of phenological and ecological responses to environmental changes [*Pettorelli et al.*, 2005] with the advantages of comprehensive ground coverage and regularly repeated observations at large scale, although atmospheric interference and a lack of biome-scale ground phenological data challenge the application of satellite-derived phenological metrics [*Badeck et al.*, 2004].

As a consequence, understanding the altitude-dependent influence of SCP on LSP and predicting future trajectories of phenological shifts are important aspects of alpine ecological studies. Obviously, snowpack characteristics are related to geographic factors such as climatic conditions, altitude, location, and slope orientation [*Dedieu et al.*, 2014; *Gobiet et al.*, 2014]. Furthermore, plant species habitats are subject to meteorological and geological conditions [*Ide and Oguma*, 2013]. Therefore, we hypothesize that effects of snow cover on alpine phenology vary among vegetation types, terrain aspects, and specific regions with altitude. Furthermore, identifying the most sensitive regions to interannual variations in snow cover is important to understanding ecosystem responses to climate change. In this study, we examined the potential impacts of interannual snow cover variations on alpine phenology using remote sensing data and focusing on natural vegetation types and geographical factors. The goals of this study are (i) to investigate how snow cover phenology (SCP) and land surface phenology (LSP) in the Alps varied between 2003 and 2014, (ii) to check for altitude-dependent changes in SCP and LSP, and (iii) to test temporal correlation between SCP and LSP metrics for the whole Alps, for specific subregions, and with variation in altitude and across different terrain aspects.

2. Material and Methods

2.1. Study Area Description

The study area is the central European Alps region, whose borders are defined by the Alpine Convention (http://www.alpconv.org/, accessed February 2017). This region is centrally located on the European continent and covers 168′252 km^2 (Figure 1a), i.e., 88.2% of the entire Alps (5.8°E–14.2°E, 43.8°N–48.2°N). The area is dominated by a typical alpine climate [*Brunetti et al.*, 2009] and commonly separated into four climatic

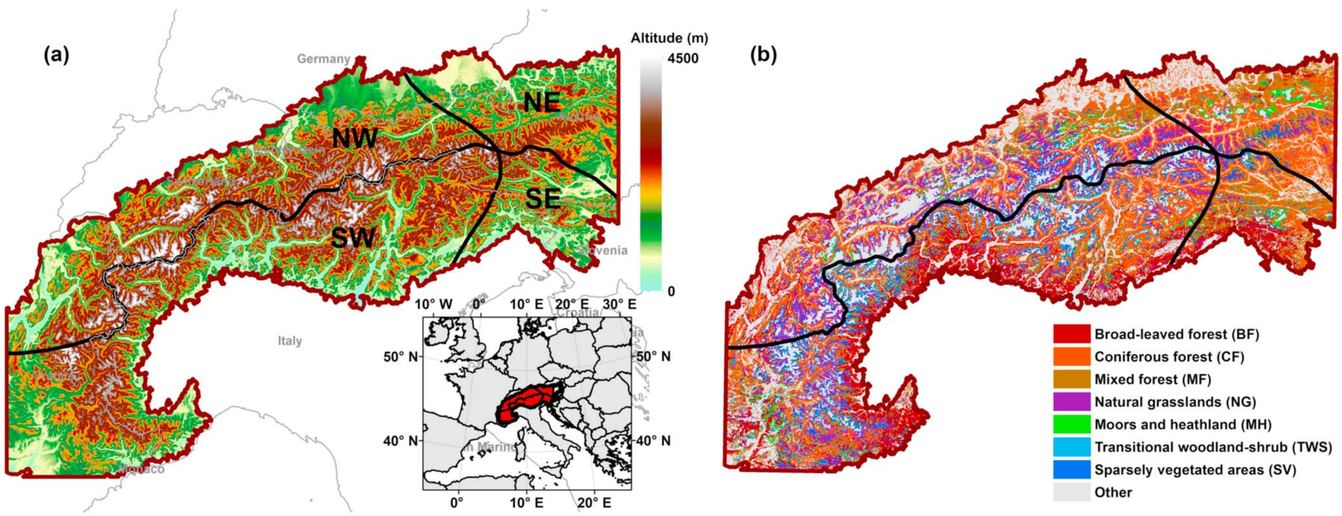

Figure 1. (a) Altitudes and (b) natural vegetation types of the study region. The dark red area (inset) delineates the study area; the black lines indicate the subdivision into four subregions (NW, NE, SW, and SE) following *Auer et al.* [2007].

subregions [*Auer et al.*, 2007]: north-west (NW; temperate westerly, oceanic features; 53′691 km^2, 32% of total area), north-east (NE; temperate westerly, continental features; 23′547 km^2, 14%), south-east (SE; mediterranean subtropical, continental features; 15′082 km^2, 9%) and south-west (SW; mediterranean subtropical, oceanic features; 75′932 km^2, 45%). The delineation of climatic subregions was defined according to the statistical regionalization of different climate elements such as precipitation and temperature as obtained from Historical Instrumental Climatological Surface Time Series of The Greater Alpine Region (HISTALP) [*Auer et al.*, 2007]. The subregions are assumed to reflect different snow-vegetation correlation regimes. The mean annual accumulative precipitation (between 2003 and 2014) ranges between 1100 and 1400 mm, with maximum values occurring at lower altitudes of the SE. The mean annual temperature (between 2003 and 2014) ranges from −5°C to 12°C in lower altitudinal zones across the study region. The Alps are subject to strong topographic variability [*Auer et al.*, 2007; *Scherrer et al.*, 2004]. The area is characterized by extensive lowlands, deeply incised valleys, and highest peaks ranging to more than 4800 m above sea level (asl). Natural vegetation (NV) covers 68.5% of the study area (Figure 1b). The predominant NV cover types in the study region are natural grasslands (15.5% of NV) and forests (64.1% of NV, including broad-leaved forest, coniferous forest, and mixed forest).

2.2. Snow Cover Phenology (SCP)

Moderate Resolution Imaging Spectroradiometer (MODIS) snow data products with a spatial resolution of 250 m were used to derive snow cover phenology (SCP) for 12 water years (WY, running from 1 October to 30 September of the following calendar year) between 2002 and 2014 for the European Alps region, including cloud removal. First snow fall (FSF) was defined as the first date in the WY when a pixel is snow covered; last snow day (LSD) is the last date in the WY when a pixel is snow covered; snow cover duration (SCD) is the total number of dates in the WY when pixels are snow covered. *Paudel and Andersen* [2013] calculated the first snow appearance day and the last snow free day given several snow cycles in Nepal Trans Himalaya. For the intermittent snow cover and potential late season transient snow fall events which occur often in the Alps [*Hüsler et al.*, 2014], we adopted the methodology used by *Paudel and Andersen* [2013] mostly for its simplicity in the calculation of the FSF and LSD. FSF, LSD, and SCD were derived from snow maps obtained from MODIS/Terra data using a novel algorithm developed by European Academy of Bolzano, Italy, in order to take into account the specific characteristics of mountain areas. The two main characteristics of the algorithm are the improved ground resolution of 250 m and a tailored topographic correction [*Dietz et al.*, 2012; *Notarnicola et al.*, 2013a, 2013b].

The daily availability of snow maps allowed the calculation of SCD without gaps (Figure S1 in the supporting information). For each pixel of the snow map, the implemented algorithm extracted the first date as FSF when there is snow. With the proposed approach, the FSF calculation was also taking into account the sporadic snowfall in the early fall. Consequently, it did not always refer to the starting date of the continuous winter snow covered period. LSD provides useful information about the melting process. To calculate LSD, the algorithm extracted from the time series of snow maps of every WY the last day in which the pixels were snow covered. Furthermore, in order to eliminate erroneous pixels due to misclassification, the final maps of FSF and LSD were filtered to remove pixels where (i) the FSF date was in the range between day of (calendar) year (DOY) 91 (1 April) and DOY 181 (30 June) and (ii) the SCD was <10. The same approach was used to extract FSF and LSD dates. Full details about the SCP derivation procedure are provided in Text S1 in the supporting information.

The uncertainty layer was used primarily during the validation of our snow products when we compared the snow maps with ground data [*Notarnicola et al.*, 2013a, 2013b]. This was done especially in difficult cases such as snow in forest and snow under critical illumination conditions [*Thirel et al.*, 2012]. From this comparison, it emerged as well that the uncertainty layer can provide some false alarm especially in certain cloud condition which may be spectrally similar to snow cover. For this reason, we introduced a further check based on the temporal variability of the pixel in the determination of the snow phenology. This is done for the snow cover duration, thanks to a moving window used to calculate the number of days with snow cover (Figure S1).

2.3. Land Surface Phenology (LSP)

MODIS MOD13Q1-version 005 normalized difference vegetation index (NDVI) data were used to derive yearly LSP metrics for start of season, endof season, and length of season (SOS, EOS and LOS, respectively) on a pixel-by-pixel basis. NDVI is one of the most widely used indices for monitoring of vegetation phenological events at various scales [*Cleland et al.*, 2007; *Fisher et al.*, 2006; *Piao et al.*, 2006]. The available MOD13Q1 images for the study period of 2003–2014 (276 in total) were 16 day composites with 250 m spatial resolution and included corresponding quality and day-of-observation information. Several studies mention that snow in vicinity of green vegetation may lead to errors when detecting vegetation greenness [*Jönsson et al.*, 2010; *Quaife and Lewis*, 2010]. Therefore, snow dynamics might relate to or influence satellite monitoring of vegetation phenology [*Jönsson et al.*, 2010; *White et al.*, 2009]. These MODIS NDVI images were transformed from the native sinusoidal projection into the universal transverse Mercator 32 projection. For quality assurance (QA) of the MODIS NDVI values and maximum value composite (MVC) data sets, we used MOD13Q1 Bands 2 and 10, which contain detailed QA (flag values of Band $2 \leq 12$ were selected based on the quality statistical results), and MVC information (16 bit binary) to generate higher-quality, cloud-free NDVI images.

To each annual time series of NDVI data, we first applied harmonic analysis to interpolate between observations, and taking into account the day of observation within each compositing window. Among the different SOS indicators that have been used in previous LSP literature, we chose the Midpoint-pixel method based on the comprehensive study of *White et al.* [2009], who found it to be better related to phenological observations across North America than other commonly used indicators. This method was also used in previous studies over Europe at coarser resolution [*Garonna et al.*, 2014]. Midpoint-pixel is a relative threshold method which defines SOS as the day when NDVI reaches half its annual range (i.e., the midpoint). The EOS was then defined as the day at which NDVI reaches the midpoint again in the calendar year, and the LOS is the number of days between SOS and EOS. SOS and EOS are always expressed in day of (calendar) year (DOY) and LOS in days.

2.4. Land Cover Data, Digital Terrain Model, and Climatologies

The CORINE Land Cover 2000 seamless vector data of the Copernicus Land Monitoring Service (http://land.copernicus.eu/, accessed February 2017) were used to stratify our results. This product is derived without the input of NDVI data, which was a crucial criteria in our choice of a land cover product to stratify our results. We assumed that every pixel belongs to one single vegetation type (reference land cover) and no changes in vegetation cover in the study region occurred over the study period of 2003–2014. Seven vegetated land cover types (i.e., broad-leaved forest (BF), coniferous forest (CF), mixed forest (MF), natural grasslands (NG), moors and heathland (MH), transitional woodland-shrub (TWS), and sparsely vegetated areas (SV)) were identified to assess the correlation of snow cover variation with alpine phenology. Topographic information at a 1 arc sec scale (30 m) obtained from the European Environment Agency was used to generate a digital elevation model (DEM) and to derive terrain information, which includes north facing (NF), east (EF), south (SF), and west facing (WF) terrain aspects. Gridded data sets with 8 km resolution of monthly precipitation

[*Efthymiadis et al.*, 2006] and temperature [*Chimani et al.*, 2013] from 2003 to 2014 were collected from HISTALP (http://www.zamg.ac.at/, accessed February 2017). All data products were resampled to a 250 m grid to match the spatial resolution of the SCP and LSP metrics, except for the climatology maps (1 km grid).

2.5. Altitude-Dependent Analysis

The altitude-dependent analysis consisted of selecting distinct zones within a 100 m altitudinal band with an altitudinal resolution of 50 m (up to 3000 m asl, corresponding to the altitude range experiencing seasonal snow and natural vegetation cover) across the entire study area. SCP and LSP metrics were averaged within each 100 m altitudinal band, for each of the 12 years of the study period. Following this step, the existence of potential changes in SCP and LSP (significance defined as $p < 0.001$) were examined by altitudinal band (100 m) using a simple linear regression. The trends of SCP and LSP were calculated by employing a simple linear regression (significance defined as $p < 0.05$) on a pixel basis over time. Interannual differences (Δ) of SCP and LSP were described for each pixel as the value of the current year minus the value of the preceding year. We assumed that alpine phenology correlates with time and duration of snow cover. Correlation coefficients between interannual differences of preseason (running from 1 October to the following SOS) snow cover (ΔLSD and ΔSCD) and alpine phenology (ΔSOS and ΔLOS) were obtained using Spearman's correlation. Spearman's correlation between ΔFSF and ΔEOS was also employed to identify the correlation between the first day of snow fall and end of season in the same season. The 250 m grids of SCP and LSP and the statistical results were intersected with the 250 m DEM, terrain aspect, subregions, and vegetation type-maps. Pixels with (i) SCD lower than 10 days or larger than 360 days, (ii) less than 1% proportion of each vegetation type, and (iii) a percentage of significant correlation lower than 5% were masked out at each altitudinal band. SCP and LSP metrics were investigated for different terrain aspects (i.e., NF, EF, SF, and WF) along the altitudinal bands. Altitude-dependent mean and trends of winter (December, January, and February) precipitation and temperature were used to analyze the meteorological environment of the four study regions. Image data processing was performed with ArcGIS (v10.0, Environmental Systems Research Institute, USA), ENVI/IDL (v4.8, EXELIS Inc., McLean, VA, USA), and statistical analysis was performed using R (v3.2.3).

3. Results

3.1. Characterization and Temporal Changes in Snow Cover Phenology (SCP) and Land Surface Phenology (LSP) Metrics Between 2003 and 2014

The distribution of natural vegetation types in the Alps and its variation with altitude are presented in Figure 2a. High altitudes (>2000 m asl) are dominated by natural grasslands (NG) and sparsely vegetated areas (SV). At midaltitudes (1000–2000 m asl), NG and forest (broad-leaved forest (BF), coniferous forest (CF), and mixed forest (MF)) are the major vegetation types, together with moors and heathland (MH) and transitional woodland-shrub (TWS). The low altitudes (<1000 m asl) are mainly covered by forest (BF, CF, and MF). Most of the natural vegetation grows between 500 and 2500 m asl (Figure 2b). The amount of natural vegetation in the western subregions (27.9% in north-west (NW) and 47.8% in south-west (SW)), being influenced by oceanic climate features, is higher than in the eastern Alps (14.2% in north-east (NE) and 10.0% in south-east (SE)), which are subject to a more continental climate regime. The altitudinal range of natural vegetation (mainly between 600–2200 m asl) is smaller in the eastern Alps (NE and SE) than in the western Alps (NW and SW).

At the same high altitude, the mean snow cover duration (SCD) is higher in the northern Alps than in the southern Alps, and in the eastern as compared to the western Alps (Figure 2c). The first snow fall (FSF) is earlier, while the last snow day (LSD) is later in the northern than in the southern Alps. At altitudes lower than 1500 m asl, the start of season (SOS) is earlier, the end of season (EOS) is later, and the length of season (LOS) is shorter in the northern than in the southern Alps. Above 1500 m asl, the opposite is true. The SOS is earlier, the EOS is later, and the LOS is longer in the western than in the eastern Alps. The spatial patterns of SCP (i.e., FSF, LSD, and SCD) and LSP (i.e., SOS, EOS, and LOS) among the four main climatic subregions of the Alps are shown in Figures S2 and S3.

Simple linear regression results show significant ($p < 0.001$) change in SCP and LSP with altitude. On average, FSF advances 1.28 (±0.01) days/50 m from 1000 to 3000 m asl, LSD delays 3.21 (±0.12) days/50 m, and SCD increases 5.65 (±0.14) days/50 m from 0 to 3000 m asl. SOS delays 1.65 (±0.04) days/50 m, and LOS shrinks

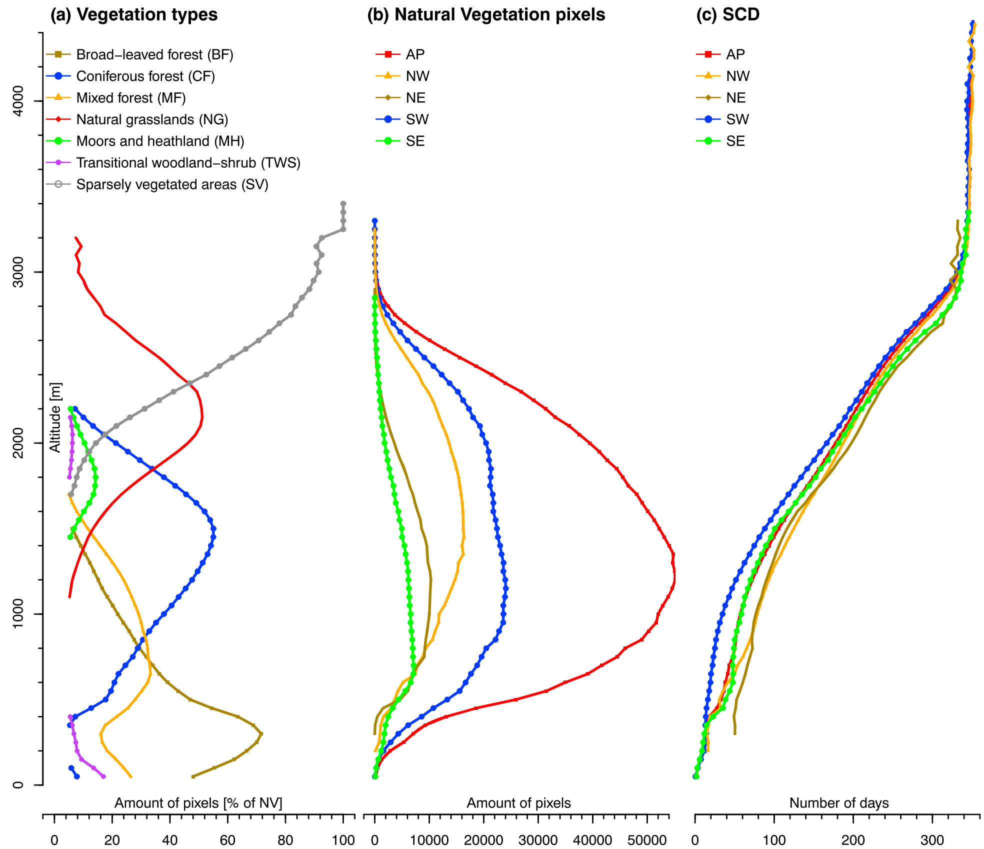

Figure 2. (a) Altitude-dependent distribution and percentage of natural vegetation types (% of NV], (b) altitude-dependent amount of natural vegetation pixels for the entire study area (AP) and the four subregions (NW, NE, SW, and SE), and (c) altitude-dependent amount of days of mean annual SCD for the entire study area (AP) and the four subregions (NW, NE, SW, and SE).

1.65 (±0.07) days/50 m from 500 to 3000 m asl with altitude increase for the entire study area. EOS advances 0.91 (±0.02) days/50 m from 1500 to 3000 m asl but shows no consistent trends in forest dominated altitudes below 1500 m. There are no apparent differences in SCP and LSP change with altitude between the four subregions (Table S1 in the supporting information), except for the SW, where the SOS shows a slight delay (0.49 days/50 m between an altitudinal range of 500–3000 m asl) compared to the other subregions.

Over the 12 investigated years, less than 3% of all pixels show a significant trend ($p < 0.05$) in SCP and LSP metrics across the entire study area. More precisely, 2.9% of pixels showed a significant delay in FSF (average of 0.98 d/yr), 1.0% of pixels showed a delay in LSD (average of 0.99 d/yr), and 2.0% of pixels showed an extension of SCD (average of 0.98 d/yr). For LSP, SOS advanced for 2.0% of pixels (averaging 0.40 d/yr), EOS delayed for 3.2% of pixels (averaging 2.17 d/yr), and LOS extended for 3.2% of pixels (averaging 2.53 d/yr) across the entire study area. These trends are similar across the four subregions (Table S2). The temporal trends and corresponding percentage of pixels with significance of SCP and LSP are presented in Figures S2 and S3.

Neither winter temperature nor precipitation shows significant trends for the period 2002–2014. The mean winter (December, January, and February) temperature showed no significant trend ($p < 0.05$), and 10.0% of the study area showed an average increase of 12.69 mm/yr in winter precipitation over the study period. The mean winter temperature and precipitation changes with altitude are presented in Figure S4.

3.2. Correlation Between ΔSCP and ΔLSP Across the Alps and in Subregions

Figure 3 shows the spatial patterns of the correlation coefficient R between ΔSCD and ΔSOS and between ΔSCD and ΔLOS across the entire study area. We found 25.3% of the considered pixels to have a significant correlation ($p < 0.05$) between ΔSCD and ΔSOS across the entire study area (Figure 3a), with a mean correlation of $R = 0.59$. The vast majority of pixels with a significant correlation between ΔSCD and ΔSOS show

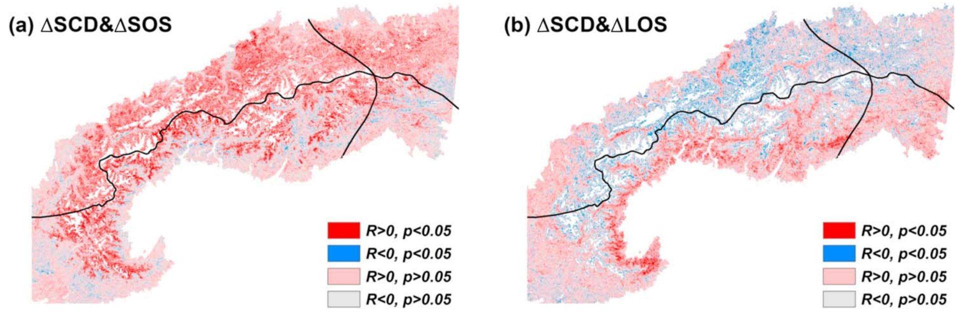

Figure 3. Correlation analysis between (a) ΔSCD and ΔSOS and (b) ΔSCD and ΔLOS across the entire study area.

positive correlation (i.e., 23.3%), and 2.0% show negative correlation between the two variables. Pixels with a negative correlation coefficient were mainly found in the southern Alps (SW and SE). Both the extent and magnitude of the correlations found were higher in the northern than in the southern subregions (Table 1). For instance, the average R across the southern Alps was 0.48, as opposed to 0.68 in the northern Alps (Table 1). The ΔSOS of the high altitudinal vegetation types (NG, MH, and SV) have stronger correlation with ΔSCD and a higher corresponding percentage of significant pixels than in the case of the low altitudinal forest (BF, CF, and MF) (Table 1). A total of 41.4% NG, 34.0% MH, and 42.2% SV show strong correlation ($R > 0.68$) between ΔSOS and ΔSCD, especially 48.0%, 43.3% and 48.1% of these vegetation types present in NW. Less than 10% BF shows significant correlation between ΔSCD and ΔSOS in the entire study area, but a higher amount of 23.3% in NE (Table 1).

Pixels of NV (15.3%) (10.0% show negative and 5.3% show positive correlation) were found to have a significant correlation between ΔSCD and ΔLOS for the entire study region (Figure 3b). Stronger mean negative correlations (−0.52 in NW and −0.49 in NE) were found in the northern Alps, compared to the mean correlations (0.08 in SW and 0.19 in SE) found in the southern Alps. More pixels with significant correlation were found in the western (16.1% in SW and 16.6% in NW) than in the eastern Alps (12.0% in NE and 13.3% in SE). Most pixels with a positive correlation were found in the southern Alps. The correlation between ΔSCD and ΔLOS of the high altitudinal vegetation types (NG and SV), as well as the corresponding percentage of significant pixels, is higher than for low altitudinal vegetation types (BF, CF, and MF) (Table 1), except for BF in SW.

Concerning LSD, only 8.8% of all pixels show a significant correlation ($p < 0.05$) between ΔLSD and ΔSOS and 8.3% of all pixels between ΔLSD and ΔLOS, respectively. Both ΔSOS and ΔLOS show low correlation with ΔLSD in middle and low altitudinal regions ($|R| < 0.1$, below 2000 m asl) and low to moderate correlations in high altitudinal regions ($|R| < 0.4$, above 2000 m asl) across the entire study area. Also, only 7.8% of all pixels show a significant correlation ($p < 0.05$) between ΔFSF and ΔEOS ($|R| < 0.1$, above 1000 m asl; $|R| < 0.3$, below 1000 m asl). The correlation of ΔSCD with ΔSOS and ΔLOS illustrates the importance of the influence of SCD on alpine phenology. Therefore, further analysis focuses on the correlation of ΔSCD with ΔSOS and ΔLOS, given the weak correlations and low percentage of significant pixels between ΔLSD and ΔSOS/ΔLOS, and between ΔLSD and ΔFSF/ΔEOS. The spatial pattern of the correlation coefficient R between ΔSCP and

Table 1. Mean Significant Correlation Coefficient R Between ΔSCD and ΔSOS and Between ΔSCD and ΔLOS for Seven Vegetation Types (BF, CF, MF, NG, MH, TWS, and SV) and Corresponding Amount of Significant Pixels (% of Total) for the Entire Study Area (AP) and the Four Subregions (NW, NE, SW, and SE)

	ΔSOS and ΔSCD (R; % of Total)					ΔSCD and ΔLOS (R; % of Total)				
Vegetation Class (% Cover)	AP	NW	NE	SW	SE	AP	NW	NE	SW	SE
BF (15.0)	0.20;9.9	0.48;14.0	0.68;23.3	0.02;8.9	0.14;8.8	0.51;18.6	0.17;11.1	0.05;8.7	0.57;21.2	0.34;13.7
CF (32.9)	0.55;22.1	0.68;28.9	0.56;23.4	0.46;18.4	0.02;12.3	−0.29;12.1	−0.49;14.2	−0.47;12.2	−0.07;10.7	0.14;11.0
MF (16.1)	0.45;18.7	0.65;25.8	0.68;27.5	0.06;12.1	−0.12;10.3	0.17;13.8	−0.16;12.1	−0.42;11.0	0.48;17.0	0.45;14.1
NG (17.4)	0.70;41.4	0.73;48.0	0.73;34.3	0.67;37.6	0.68;35.8	−0.52;17.8	−0.68;20.7	−0.67;13.3	−0.34;16.4	−0.35;16.0
MH (5.2)	0.68;34.0	0.73;43.4	0.72;31.6	0.62;31.0	0.65;28.1	−0.57;16.3	−0.67;21.8	−0.65;13.0	−0.45;15.8	−0.54;12.8
TWS (4.1)	0.53;24.1	0.70;32.8	0.64;32.2	0.52;24.0	0.15;13.9	−0.01;15.2	−0.48;14.1	−0.52;13.7	0.02;15.3	0.25;14.5
SV (9.3)	0.71;42.3	0.73;48.1	0.71;26.5	0.70;41.3	0.64;27.3	−0.61;20.5	−0.69;23.1	−0.64;12.8	−0.56;20.0	−0.44;14.4
NV	0.59;25.3	0.70;34.9	0.64;26.6	0.51;21. 6	0.25;14.2	−0.15;15.3	−0.52;16.6	−0.49;12.0	0.08;16.1	0.19;13.3

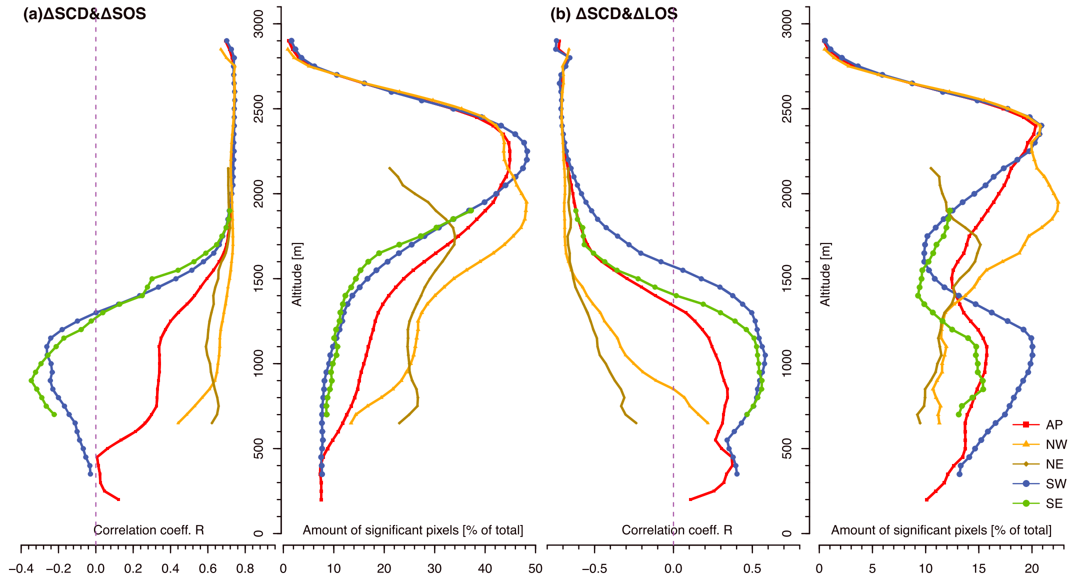

Figure 4. Altitudinal variation in (a, left, and b, left) correlation coefficient R and (a, right, and b, right) corresponding amount of pixels (% of total) with a significant correlation between ΔSCD and ΔSOS (Figure 4a) and ΔSCD and ΔLOS (Figure 4b) across the entire study area (AP) and averaged by subregion (NW, NE, SW, and SE). The dashed purple lines represent a correlation coefficient of 0. The corresponding figures for seven natural vegetation types (BF, CF, MF, NG, MH, TWS, and SV) across the entire study area (AP) and the four subregions (NW, SE, SW, and NE) are presented in Figures S6 and S7.

ΔLSP and the corresponding significant pixels across the entire study area for the period of 2003–2014 are summarised in Figure S5.

3.3. Correlation Between ΔSCP and ΔLSP With Variation in Altitude

In the period of 2003–2014, the correlations between ΔSCD and ΔSOS and between ΔSCD and ΔLOS were strongest at high altitudes (> 2000 m asl) (Figure 4). All four subregions show the same pattern: a strong positive correlation ($R > 0.7$) between ΔSCD and ΔSOS and a strong negative correlation ($R < -0.6$) between ΔSCD and ΔLOS. However, the differences among the four subregions are clearly present in middle and low altitudinal zones (Figure 4). Subregional differences in all correlations were only present at mid and low altitudes.

More precisely, above 1800 m asl, where vegetation is predominantly MF, NG, and SV and where SCD is greater than 150 days, the correlation coefficient R of ΔSCD and ΔSOS is greater than 0.70 (Figure 4a). At these altitudes, about 30–50% of natural vegetation areas have a high positive correlation for the entire study region, with almost no differences between the four subregions. In altitudinal regions above 1800 m asl, the positive correlation between ΔSCD and ΔSOS turns to stable and appears largely the same between the four subregions. At high altitudes, the percentage of pixels with significant positive correlation peaks around 2300 m asl, before dramatically declining with altitude where SCD exceeds 220 days. The positive values of the correlation coefficient R of ΔSCD and ΔSOS slightly increase with altitude from 600 to 1800 m. asl in the northern Alps (NW and NE). From 1300 to 1800 m asl in the southern Alps (SW and SE), the correlation coefficient R of ΔSCD and ΔSOS strongly increases with altitude. Around 1300 m above sea level (asl) in the southern Alps, where vegetation is dominated by forest (BF, CF, and MF), the negative correlation turns to positive with increasing altitude. The strongest negative ($R < -0.3$) correlations of ΔSCD and ΔSOS are observed at low altitudes (800 to 1200 m asl) in the southern Alps, where the SCD is less than 60 days.

Concerning the correlation between ΔSCD and ΔLOS in the altitudinal zones dominated by NG and SV (above 2250 m asl, where SCD is greater than 280 days), high negative values of the correlation coefficient R around -0.65 can be observed (Figure 4b). Natural vegetation pixels at these high altitudes show high negative correlations between ΔSCD and ΔLOS for the entire study region and no differences between the four subregions. Above 2250 m asl, the negative correlation between ΔSCD and ΔLOS turns to stable and appears

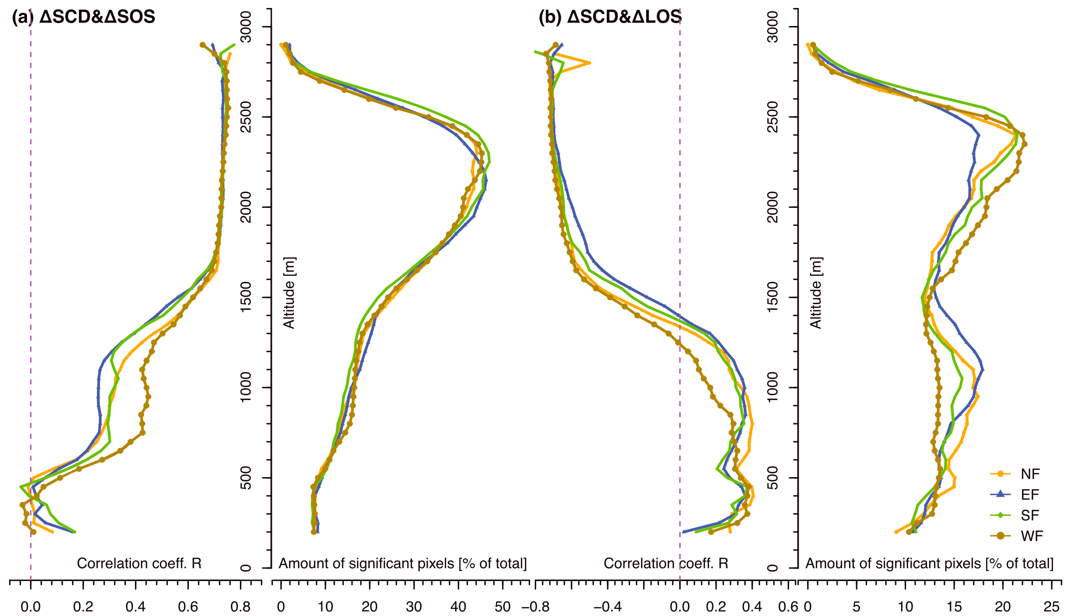

Figure 5. Altitudinal variation in (a, left, and b, left) correlation coefficient R and (a, right, and b, right) corresponding amount of pixels (% of total) with a significant correlation between ΔSCD and ΔSOS (Figure 5a) and ΔSCD and ΔLOS (Figure 5b) for north (NF), west (WF), south (SF), and east facing (EF) terrains of natural vegetation (NV) across the entire study area (AP). The dashed purple lines represent correlation coefficients of 0.

almost the same between the four subregions. The percentage of significant pixels of negative correlation peaks around 2400 m asl but declines with altitude where SCD becomes more than 240 days. In altitudinal regions dominated by forest (BF, CF, and MF), the correlation between ΔSCD and ΔLOS turns from positive to negative at 800 m asl in NW, at 1550 m asl in SW, and at 1400 m asl in SE with increasing altitude. A positive correlation between ΔSCD and ΔLOS was mainly found at middle and low altitudes (<1500 m asl with SCD less than 100 days) in the southern Alps (SW and SE).

3.4. Correlation Between ΔSCP and ΔLSP With Variation in Terrain Aspect

At high altitudes above 1900 m asl, where the dominant vegetation types are MF, NG, and SV, there is no apparent difference in the correlation between ΔSCD and ΔSOS among the four main terrain aspects (Figure 5a). At low and middle altitudes (below 1800 m asl), there are differences in the correlation between ΔSCD and ΔSOS among the four aspects: north and west facing terrain aspects show slightly higher positive correlation values than south and east facing terrain aspects. The corresponding percentage of pixels with a significant correlation is similar among the four terrain aspects but differs with altitude.

The same pattern is true for the correlation coefficient *R* between ΔSCD and ΔLOS and the corresponding percentage of significant pixels, which show no major difference among the four terrain aspects above 2400 m asl (Figure 5b). Slightly higher negative correlations between ΔSCD and ΔLOS can be found for north and west facing terrain compared to south and east facing terrain for altitudes ranging from 1400 to 2200 m asl across the entire study area. Low altitudes (<1000 m asl) only show slight differences among the four terrain aspects.

In general, the differences in correlations between ΔSCD and ΔSOS and between ΔSCD and ΔLOS and the corresponding percentage of significant pixels between the four terrain aspects are more pronounced at low and middle altitudes and they tend to become smaller and even disappear toward high altitudes for the entire study area (Figure 5) and the four subregions (Figure S8). For each vegetation type, highest *R* values and corresponding percentage of pixels with significant correlation are present in west and north facing terrains, as compared to south and east facing terrains for the entire study area and the four subregions (Table S3).

4. Discussion

4.1. Characterization and Temporal Changes in Snow Cover Phenology (SCP) and Land Surface Phenology (LSP) Metrics Between 2003 and 2014

Our results indicate that SCP metrics (i.e., first snow fall (FSF), last snow day (LSD), and snow cover duration (SCD)) vary considerably between the four subregions (north-west (NW), north-east (NE), south-west (SW), and south-east (SE)) of the Alps. The findings that the SCD in the SW is lower than in the NE and that regional differences in SCD disappear at higher altitudes are in agreement with *Hüsler et al.* [2014], who reported that the northern Alps had above-average SCD as compared to the southern Alps. These regional differences of SCD are presumably due to different climatic influences, such as a stronger dependency of snow cover on precipitation at higher altitudes, and a higher sensitivity of snow cover to temperature in lower regions [*Hüsler et al.*, 2014]. Our results show earlier FSF and later LSD in regions with longer SCD in the northern Alps (with more precipitation in winter) and at high altitudes (with lower freezing temperature in winter) over the past decade (Figures 2c and S2). LSP (i.e., start of season (SOS), end of season (EOS), and length of season (LOS)) shows regular distribution with coupling to SCP across study area (Figures S2 and S3). Namely, a later SOS, an earlier EOS, and a shorter LOS often occur in climatic subregions with longer SCD, and vice versa.

SCP and LSP metrics both showed significant relationship with altitude (Table S1), confirming the dependency of both snow cover and phenology on altitude [*Gottfried et al.*, 2012]. The finding that SCD increases by 5.65 (±0.14) days/50 m within 50 to 3000 m asl is in agreement with findings by *Hüsler et al.* [2014] where an increase of 5.0 days/50 m with a standard deviation of 12.5 days for the entire Alps is reported. Based on a study performed in the Berchtesgaden National Park, *Cornelius et al.* [2013] suggests that about 50% of all phenological events are significantly influenced by altitude. Despite differences in research methods and scale in our study, we find LSP to be strongly dependent on altitude across the entire Alps except for some forest-dominated low-altitude areas. This is reflected in the SOS delay with increasing altitude found across the entire study area. Our estimate of 1.65 (±0.04) days/50 m between 500 and 3000 m asl is in line with field observations by *Cornelius et al.* [2013], who found delays of 1.90 days/50 m between 680 and 1425 m asl in the northern part of the Berchtesgaden National Park in the Alps. Moreover, the linear delays of SOS with altitude in this study are similar with 1.35 days/50 m in New Hampshire [*Richardson et al.*, 2006] and 1.7 days/50 m in North Carolina [*Hwang et al.*, 2011]. In contrast to other studies over the southern Appalachians [*Hwang et al.*, 2011] and the eastern United States [*Elmore et al.*, 2012], we found that EOS advances 0.91 (±0.02) days/50 m between 1500 and 2500 m asl and LOS shrinks 2.09 (±0.07) days/50 m between 500 and 3000 m asl across our entire study area.

In our results, we found no significant trend in SCP and LSP metrics between 2003 and 2014. This was also the case for SCP over the period of 1990–2011 in previous studies [*Hüsler et al.*, 2014; *Marty*, 2008]. This is in contrast to *Chen et al.* [2015a], who reported that SCD has become shorter across European Alps from 2001 to 2014, as well as other studies reporting significant trends in recent decades in LSP over this region [*Defila and Clot*, 2005; *Stöckli and Vidale*, 2004]. However, these studies [*Defila and Clot*, 2005; *Stöckli and Vidale*, 2004] consider much longer time extents as compared to the 12 years of our study.

4.2. Correlation Between ΔSCP and ΔLSP Across the Alps and in Subregions

The finding that SCD is positively correlated with SOS but is negatively correlated with LOS across entire Alps (Figure 3 and Table 1) is a clear indication that snow cover duration influences the start and the length of vegetation phenology in alpine regions and thus plays a role in dynamic of alpine ecosystem. These results are in agreement with previous studies that demonstrated that prolonged snow cover results in a delayed and reduced growing season [*Cooper et al.*, 2011; *Jonas et al.*, 2008; *Julitta et al.*, 2014], whereas a shortened snow cover duration mostly advances and prolongs plant growth time [*Galvagno et al.*, 2013; *Wipf and Rixen*, 2010; *Wipf et al.*, 2009]. Furthermore, *Dorrepaal et al.* [2003] stated that increased winter snow cover had a positive effect on the production of *Sphagnum fuscum* in Abisko, Sweden. *Yu et al.* [2013] found that both winter and spring snow depths have an impact on SOS timing. These studies partially confirm that snow cover affects alpine phenology.

Our study includes LSD and FSF metrics, which do not necessarily represent the last and first date of the continuously snow covered winter period but allow us to account for potential late season transient snowfall events occurring in the Alps. Our results (section 3.2) indicate that last snow day and first snow fall have no influence on alpine phenology. In another study over the Nepal Trans Himalayan region, *Paudel and Andersen* [2013] used similar metrics but reported high correlations between last snow-free day and SOS over large areas and between first snow day and EOS at very high altitudes. This can be due to other factors such as different climatological and meteorological conditions. More precisely, our results only show low correlation coefficients ($|R| < 0.3$) between ΔLSD and ΔSOS and between ΔLSD and ΔLOS and a small amount of corresponding significant pixels (<8% of total) across the entire study area. The correlations of ΔLSD with ΔSOS and ΔLOS at high altitudes ($0.3 < |R| < 0.4$) are slightly higher than the correlations at mid and low altitudes ($|R| < 0.3$). Moreover, our results show no correlation between ΔFSF and ΔEOS. This may be due to the fact that the FSF and LSD are most meaningful in regions with continuous seasonal snow cover, other than in regions with multiple late season transient snowfall [*Hüsler et al.*, 2014]. Therefore, we conclude that SCD, rather than LSD or FSF, correlates with alpine phenology and largely affects it across altitude. Furthermore, late season transient snowfall events may only have limited influence on the growth of alpine vegetation and the dynamics of alpine ecosystem.

Our results show that the correlations between ΔSCD and ΔSOS and between ΔSCD and ΔLOS differ considerably between the four subregions (Figure 3 and Table 1), being generally stronger in the northern than in the southern Alpine subregions. These findings are in agreement with the fact that the correlation strength between SCD and onset of spring is dependent on the climate of a geographical region [*Jönsson et al.*, 2010]. We conclude that the correlation between SCD and alpine phenology is stronger in geographical regions with longer SCD than in regions with shorter SCD. Our study goes one step further in showing that the correlation between ΔSCD and ΔSOS and between ΔSCD and ΔLOS vary between vegetation types (Table 1). We found that ΔSCD has a strong positive correlation with ΔSOS and a negative correlation with ΔLOS for NG, MH, SV, and midaltitude TWS (Table 1 and Figures S6 and S7). These results indicate that a later start of growing season and a shorter length of growing season are always in parallel with a longer snow cover duration in high and middle altitudinal vegetation types, and vice versa. These findings support the suggestion by *Julitta et al.* [2014] that snow cover plays an important role in determining the start of phenological development in alpine grasslands and agree with the finding by *Galvagno et al.* [2013] that snow cover limits the length of the growing season in high-altitude grasslands. *Yu et al.* [2013] report that the winter snow depth has stronger effect on grasslands and shrubs than on broadleaf deciduous forests and needleleaf forests in temperate China, which is what we also find for the Alps. Our results provide evidence that SCD is correlated with forest phenology in middle and low altitudes across the Alps. Indeed, the phenology of forests (i.e., 10–22% of the total area of BF, CF and MF) and low-altitude TWS significantly correlates ($|R| < 0.5$) with snow cover duration at middle and low altitudes (Figures S6 and S7). Although temperature strongly regulates the start of the growing season of both temperate deciduous broadleaf and coniferous forest [*Yu et al.*, 2013], our results consequently support the suggestion that phenological events of most temperate tree species are not solely driven by air temperature [*Yu et al.*, 2013] but also by snow cover duration. Furthermore, in European Alps, the dynamic of forest ecosystem could be affected by the variation of interannual snow cover duration.

Our choice of land cover data set entails that changes in land cover type within the study period are not taken into account in our analysis. However, excluding pixels with land cover change between 2000 and 2012 had no significant influence on our results.

4.3. Correlation Between ΔSCP and ΔLSP With Variation in Altitude

Together with other environmental factors, snow is one of the essential environmental parameters controlling high-altitude alpine phenology [*Cornelius et al.*, 2013; *Wipf et al.*, 2009; *Zeeman et al.*, 2017]. The positive correlation between ΔSCD and ΔSOS and the negative correlation between ΔSCD and ΔLOS, both of which were found over high-altitude regions in Figure 4, indicate that the influence of snow cover duration on the start and length of alpine phenology is strong at high altitudes. Our results are in marked agreement with *Keller et al.* [2005], who concluded that SCD largely determines the length of the growing season of the vegetation in high altitude areas of the Swiss Alps. Our findings further agree with the fact that longer SCD reduce the length of the alpine phenology cycle [*Björk and Molau*, 2007; *Cooper et al.*, 2011]. Based on a study in the Swiss Alps, *Jonas et al.* [2008] reported that locations with late snowmelt typically experience a longer snow cover season and thus attract plant communities with shorter vegetation cycles. A study by *Abeli et al.* [2011] found the inflorescence production to be significantly correlated with snow cover persistence from 1980 to 2054 m asl in the North Apennines of Italy, thus emphasizing the importance of SCD. At high altitudes, mean annual SCD was longer than 180 d/yr. Meanwhile, the declining amount of pixels with significant correlation between ΔSCD and ΔSOS and between ΔSCD and ΔLOS with altitude above 2000 m asl is shown in Figure 4. These may underpin the role of extreme temperatures, beside SCD, as a limiting factor for alpine phenology in these areas.

At midaltitudes (1000–2000 m asl), the positive correlation between ΔSCD and ΔSOS above 1300 m asl and the negative correlation between ΔSCD and ΔLOS above 1500 m asl is higher in the northern than in the southern Alps (Figure 4). Hence, it may be concluded that the correlation of SCD with midaltitude alpine phenology is stronger in regions with longer SCD. In the southern Alps, the positive correlation between ΔSCD and ΔSOS shifts to negative around 1300 m asl and the negative correlation between ΔSCD and ΔSOS shifts to positive around 1500 m asl with increasing altitude. This change in correlation is similar to *Yu et al.* [2013], who found differing impacts of winter snow depth and spring snow depth on start of growing season. With increasing snow depth, the associated effect changed from delaying start of growing season to advancing start of growing season [*Yu et al.*, 2013]. We can conclude that the variation of the influence of snow cover duration on start and length of phenology with altitude is not only in magnitude but also in characteristic. Thus, the role of snow cover in alpine ecosystem might also vary with altitude. Furthermore, our results show that the altitude at which the change in correlation sign occurs are different among the four subregions. SCD in each subregion is different around these thresholds, possibly due to subregional climate.

At low altitudes (<1000 m asl), where SCD is lower than 50 days, negative correlations between ΔSCD and ΔSOS and positive correlations between ΔSCD and ΔLOS were mainly found in the southern Alps. There, a longer SCD results in an earlier start of the growing season and therefore a longer growing season, and vice versa. This may be due to the warmer climate at low altitudes, which changes sequestration rates of soil carbon due to changes in the insulating snow depth in forest ecosystems [*Monson et al.*, 2006]. Therefore, a longer snow cover period can provide longer frost protection for plants in winter [*Desai et al.*, 2016; *Hu et al.*, 2010] and may result in more soil moisture and nutrient mobilization at the start of the growing period [*Bergeron et al.*, 2007; *Dunn et al.*, 2007]. This could explain the observed negative correlation between ΔSCD and ΔSOS and the positive correlation between ΔSCD and ΔLOS in low-altitude regions dominated by forest (<1000 m asl) in the southern Alps.

Overall, our results show that the relationship between SCD and alpine phenology varies with low altitude and midaltitude. The correlation differences between climatic subregions of the Alps are pronounced at middle and low altitudes, yet become smaller with increasing altitude and eventually disappear toward high altitudes. Our findings are in agreement with the hypothesis that the role of snow cover in alpine ecosystem varies between altitudes, vegetation types, and climate subregions. Namely, the changing in role of snow cover is depending on climate and other environmental factors such as altitude.

4.4. Correlation Between ΔSCP and ΔLSP With Variation in Terrain Aspect

Our results show that SCD on north and west facing terrains is longer than on south and east facing terrains in all altitudes. This is in parallel with higher correlation between ΔSCD and ΔSOS and between ΔSCD and ΔLOS on north than on south facing terrains and on west than on east facing terrains. These results are in agreement with previous studies reporting that the distribution of snow cover and vegetation are closely linked with terrain aspect [*Gottfried et al.*, 2012; *Keller et al.*, 2005]. The smallest SCDs occur on south facing terrains due to the influence of direct solar energy [*Keller et al.*, 2005]. Similar results were found by *Ide and Oguma* [2013], where the ratio between snow-covered and snow-free pixels recorded by digital time-lapse cameras in the northern Japanese Alps declined earlier at sites on south facing terrain slopes, as compared to sites on slopes facing other directions. South facing terrains receive more direct solar radiation resulting in shorter SCD [*Marke et al.*, 2013] and longer photoperiod length for alpine plants. Thus, these results suggest that sunshine duration influences alpine phenology, on top of SCD and variation in terrain aspect.

Concerning differences between west and east facing terrain aspects with opposite exposure to dominant atmospheric circulation patterns in winter, our results show a lower SCD on east than on the west facing terrain aspects. This may explain the correlation between ΔSCD and ΔSOS and between ΔSCD and ΔLOS on east facing terrains being lower than on west facing terrains. In general, our results reveal that correlation differences between SCD and alpine phenology due to terrain aspects are more pronounced in middle and low altitudes. In our results, these correlation differences tended to decrease at high altitudes across the entire study area.

4.5. Implications on the Relationship Between Snow Cover and Alpine Phenology Under a Climate Warming Scenario

The European Alps are expected to be particularly sensitive to climate change [*Beniston et al.*, 2003; *Gobiet et al.*, 2014]. Compared to the background global average increase of 0.7 °C in the past 100 years [*IPCC*, 2007], annual mean temperatures have increased by about 1.1 °C in the European Alps over the same period [*Böhm et al.*, 2001]. Moreover, higher-than-average increases in temperature are expected for the next decades [*IPCC*, 2007]. However, in this study, no significant change was found in mean winter temperature and cumulative precipitation over the past decade (Figure S4), but this is likely an effect of the relatively short investigated period. Other sources indicated that warming is likely to occur at approximately 0.25°C per decade until 2050 and accelerate to 0.36°C per decade toward the end of the 21st century [*Gobiet et al.*, 2014]. These temperatures are likely to cause reduction in snow fall and earlier melting of snow in spring [*Barnett et al.*, 2005], with important consequences for SCP and LSP. Thus, shorter snow cover duration might lead to earlier start of season, consequently resulting in an advancement and extension of the carbon uptake period [*Desai et al.*, 2016].

The results presented in our study indicate a strong sensitivity of ecological processes to snow cover duration associated with altitude. Specifically, the correlation between ΔSCD and ΔSOS and between ΔSCD and ΔLOS in each of the four alpine subregions and across altitudinal bands support the following: (i) increased air temperature, together with reduced snow cover, may lead to increased water stress and ultimately constrains vegetation growth [*IPCC*, 2007], and (ii) variations in seasonal snow cover may interact with air temperature and thus affect plant growth [*Yu et al.*, 2013]. As differences in the atmospheric heating of snow-covered and snow-free ecosystems are larger in spring than in autumn [*Euskirchen et al.*, 2007], and given that we found a larger area with significant correlation between ΔSCD and ΔSOS than between ΔSCD and ΔLOS, the start of alpine phenology could become more sensitive to future warming than the overall length of the growing season. Our results indicate that alpine vegetation ecosystems are particularly sensitive to future changes in snow cover at middle and high altitudes. More precisely, our results suggest that the phenology of midaltitude forests in the northern Alps, as well as in high-altitude natural grassland, may be considerably affected by future potential changes in SCD.

Furthermore, phenological shifts can lead to variations in the distribution and abundance of plant species [*Jonas et al.*, 2008]. Our results suggest that the expected changes in snow cover in the Alps would impact vegetation phenology in this region, thus reshaping the topographical distribution, species composition, and performance of alpine vegetation. These changes in performance might themselves affect other alpine processes, such as bird and herbivore migration or wildfires. On a macrolevel, the variability of snow cover phenology also influences intraannual water exchanges and land surface carbon storage. Though it remains to be tested, our results suggest that changes are more pronounced in the northern Alps and for high-altitude and midaltitude grasslands, as compared to the southern Alps and low-altitude forests.

5. Conclusions

This study examined how the spatiotemporal variability of snow cover correlates with alpine land surface phenology. Based on the analysis between snow cover phenology (SCP) and land surface phenology (LSP) in the European Alps, our findings support the hypothesis that the influence of snow cover on alpine phenology is different between climatic subregions, natural vegetation types, and terrain aspects with varying altitudinal bands. In particular, we found that snow cover duration (SCD) plays a key role in the start and length of the growing season in middle and high altitudes across the European Alps. The correlation between SCD and start/length of the growing season varies considerably with altitude. This correlation is stronger in the northern and eastern Alps than in the southern and western Alps, and it peaks at high altitudes, where natural grassland and sparse vegetation areas dominate. The altitude-dependent correlation between SCD and start/length of growing season in north and west facing terrain aspects is higher than in south and east facing terrain aspects.

We demonstrated that a change in SCD has a greater impact on alpine phenology at higher than at lower altitude, which may be due to a coupled influence of SCD with underground conditions and air temperature. Alpine phenology will react to changes in SCD with the predicted increase of global temperatures that influences and reshapes the alpine ecosystem. The magnitude of these responses will differ depending on vegetation types, climatic subregions, and topographical factors such as altitude and terrain aspect but will be more pronounced in regions with longer SCD and in higher altitudes.

Our study presented an overview on altitude-dependent correlation of snow cover with alpine phenology. Future work should address the relationship between alpine phenology and snow accumulation (e.g., winter solid precipitation, snow depth, or snow water equivalent) to explore the mechanisms driving snow-vegetation interactions in alpine regions. In addition, increased combination of ground and satellite observations for detailed long-term investigations should be envisaged.

Acknowledgments
Jing Xie is supported by the Chinese Scholarship Council (CSC). The work of Michael E Schaepman, Rogier De Jong, and Irene Garonna is supported by the University of Zurich Research Priority Program on Global Change and Biodiversity (URPP GCB). We appreciate advice on land surface phenology computation by Pascal Niklaus and Jacqueline Oehri. The principal data reported in this paper will be available for download from http://www.geo.uzh.ch/microsite/rsl-documents/research/suppl_data/Jing_Xie_JGR.zip.

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